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The main area of research for this year was improving both the output power and the tuning range of the SGDBR lasers. To improve the output power we increased the number of quantum wells in the active region from four to six. This also broadened the gain spectrum enabling a wider tuning range. Devices with up to 0.6 mW of output power and 72 nm tuning ranges were realized. Current laser results indicate that leakage current is a major factor in limiting the device performance. To eliminate the parasitic leakage paths we have begun to investigate Fe doped blocking junctions for the device. Work on the wavelength monitor has focused on an external approach, which uses a wavelength dependent coupler in conjunction with a pair of photodetectors. Initial results show better than 1 nm sensitivity over a 30 nm range. The most recent work on the laser has focussed on integrating additional components for increased functionality. We have developed a specially designed semiconductor optical amplifier that can be integrated with the laser to increase the output power to greater than 6 mW. We have also investigated SGDBR lasers with integrated electro-absorption modulators. Using a 300 μm long bulk EA modulator we have demonstrated error free data transmission at 2.5 GBit/s with a 231-1 pattern length at received powers of -32.5 dBm.

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Improved Sampled Grating DBR Widely-Tunable 1.55μm Lasers

Abstract

The main area of research for this year was improving both the output power and the tuning range of the SGDBR lasers. To improve the output power we increased the number of quantum wells in the active region from four to six. This also broadened the gain spectrum enabling a wider tuning range. Devices with up to 0.6 mW of output power and 72 nm tuning ranges were realized. Current laser results indicate that leakage current is a major factor in limiting the device performance. To eliminate the parasitic leakage paths we have begun to investigate Fe doped blocking junctions for the device. Work on the wavelength monitor has focused on an external approach, which uses a wavelength dependent coupler in conjunction with a pair of photodetectors. Initial results show better than 1 nm sensitivity over a 30 nm range. The most recent work on the laser has focussed on integrating additional components for increased functionality. We have developed a specially designed semiconductor optical amplifier that can be integrated with the laser to increase the output power to greater than 6 mW. We have also investigated SGDBR lasers with integrated electro-absorption modulators. Using a 300 μm long bulk EA modulator we have demonstrated error free data transmission at 2.5 GBit/s with a 2^{31}-1 pattern length at received powers of –32.5 dBm.

Tunable Laser Results

To achieve very wide range tuning from the SGDBR laser requires a carefully optimized mirror design and a high quality gain section with a wide spectral bandwidth. The goal in the mirror design is to optimize the tuning enhancement factor so that the largest wavelength range can be covered with the minimum amount of index tuning. Ultimately the tuning range is limited by the repeat mode spacing in the mirrors. Which is equal to the product of the peak spacings in the mirrors divided by the difference in the peak spacing. To maximize the repeat mode spacing $\Delta\lambda_{RMS}$ and minimize the maximum index tuning, which is equal to the front mirror peak spacing $\Delta\lambda_F$, we must use the minimum possible value for the difference in the mirror peak spacing $\delta\lambda_S$.

The minimum value for $\delta\lambda_S$ is set by the side mode suppression ratio which is required for the device. In order to maintain a high SMSR it is essential that the 3 dB bandwidth for the mirror reflection peaks be less than double difference in the mirror peak spacing. The bandwidth of the mirror peaks is determined by the number of sampling periods. For a mirror with a grating Kappa of 300 cm^{-1} and a 3 μm grating burst length at least 10 sampling periods are required to achieve a reflection peak bandwidth below 1 nm. However since the peak width tends to broaden somewhat during tuning we chose a minimum of 12 sampling periods for the front mirror and 17 for the back. The front mirror sampling period was 46 μm giving a peak spacing of ~7 nm and the back mirror sampling period was 43 μm giving a peak spacing of ~7.5 nm. This gave the device a tuning enhancement factor of 14 with a repeat mode spacing of 105 nm. The relatively short burst length of 3 μm was chosen to give an overall reflection envelope of 90 nm. This limited the tuning range to about 15 nm less than the tuning enhancement factor enabled. The number of quantum wells in the active section was increased to 6 to provide more gain and a wider gain bandwidth. The laser was capable of tuning quasi-continuously over 72 nm. The tuning curves are shown in Figure 1a and 1b.

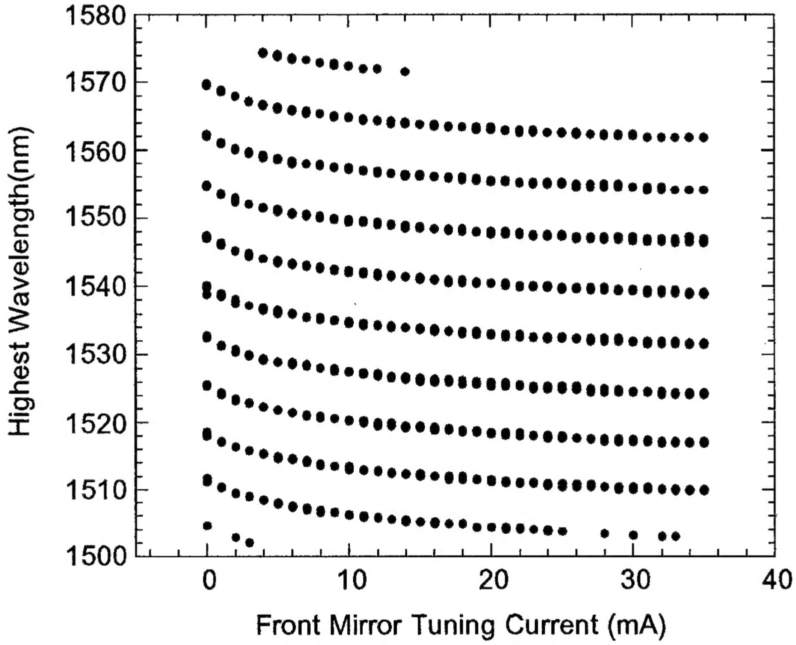

Figure 1a. Front mirror tuning curves for 72 nm quasicontinuous tuning range tested at 0.5 mA intervals from 0 to 35 mA. All points > 30 dB SMSR

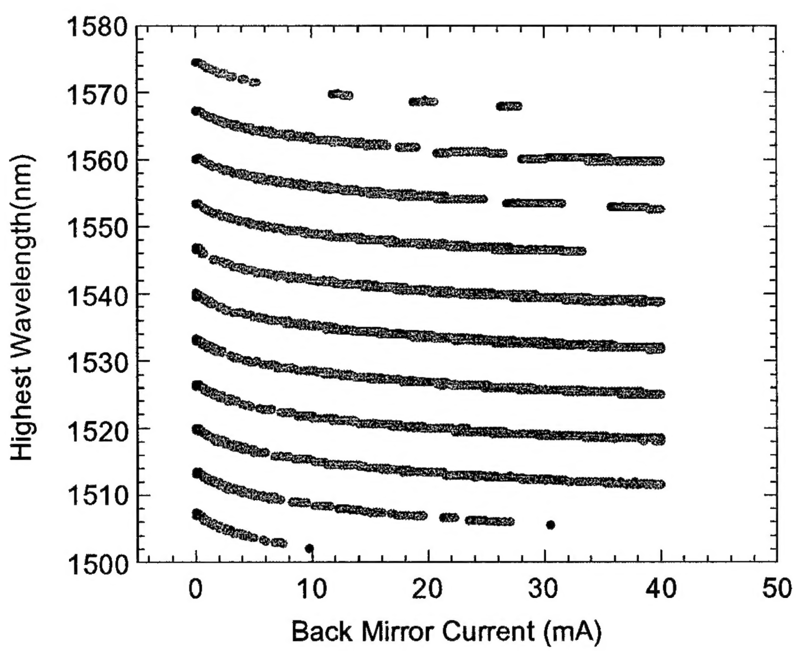

Figure 1b. Back mirror tuning curves for 72 nm quasicontinuous tuning range tested at 0.1 mA intervals from 0 to 40 mA. All points > 30 dB SMSR.

Fe Doped Blocking Junctions

The light versus current curves for the new lasers had a tendancy to roll over at fairly low current densities indicating a strong leakage path. The key to preventing leakage in the buried ridge stripe design is to use high doping levels at the parasitic P-N junction. The doping levels must be high enough that the turn on voltage for the homojunction is significantly greater than the bandgap of the active region. The problem with the SGDBR laser is that the high doping levels cause high propagation loss in the waveguide due to intervalence band absorption. Another drawback to the buried ridge stripe design is that the large parasitic P-N junction has a high capacitance which limits the modulation bandwidth of the device. Iron doped blocking junctions have the potential to provide a low leakage low capacitance structure due to their semi-insulating nature. This would enable significant improvements in both the output power and the tuning efficiency for the SGDBR. It would also increase the modulation bandwidth for the device. We have begun to investigate the conditions for growing these structures using a Biscyclopentadienyl-iron source to dope InP. The resistivity and critical voltage for a variety of Fe doping levels in 1 μm thick n-Fe-n structures are shown in Figure 2.

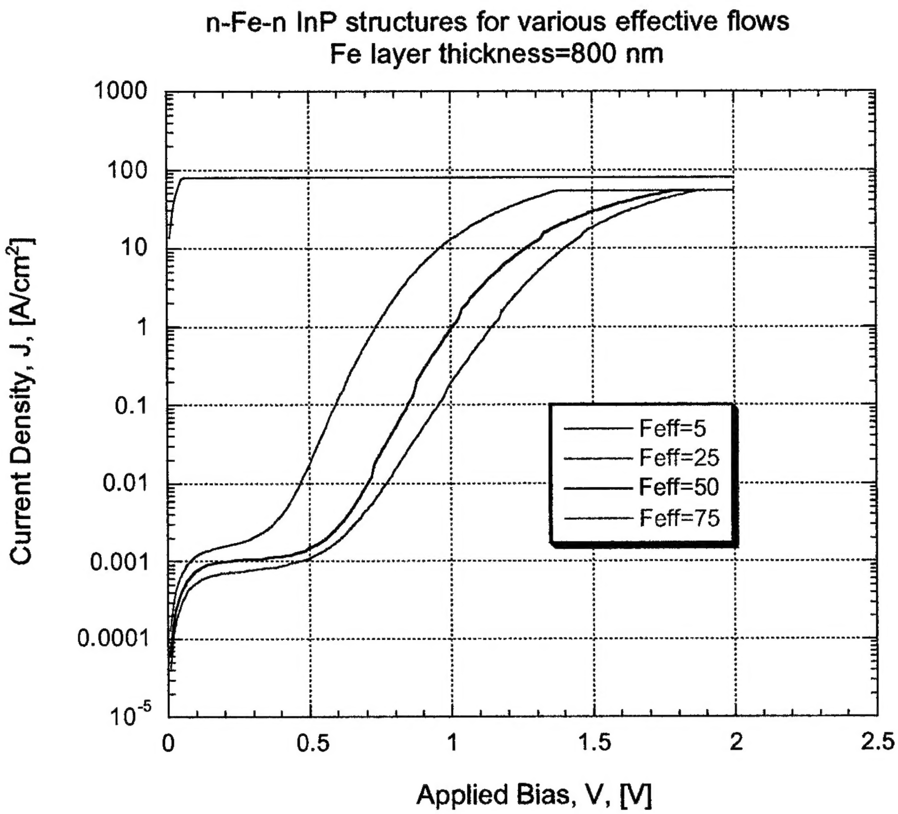

Figure 2. Resistivity for n-Fe-n InP structures grown with a variety of effective dopant flow rates. (3000Å n-type/10000Å Fe-SI/5000Å n-type).

The maximum effective flow rate which we can achieve with the current mass flow controllers is 100. It is clear from this plot that much higher effective flows will be required to make the material semi-insulating. The current critical voltage is around 0.5V. This will have to be increased to more than 2V for effective blocking. The intended growth structure for the semi-insulting device is shown in Figure 3 with a scanning electron micrograph of the device cross section in Figure 4.. This structure requires a masked regrowth for the blocking junction follwed by an additional capping regrowth for the upper contact layer.

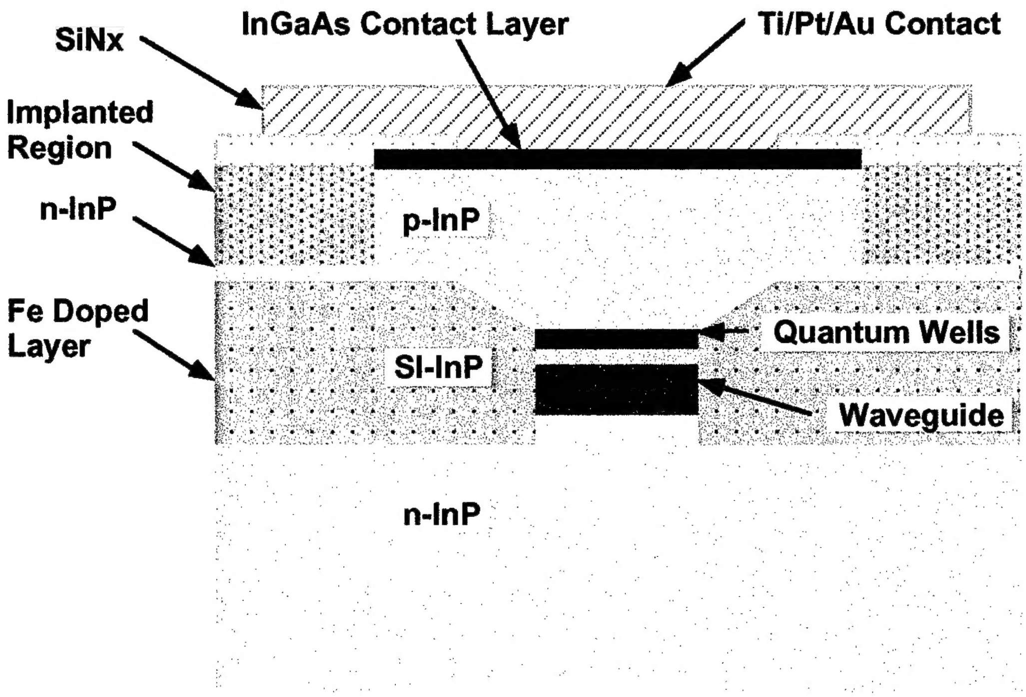

Figure 3. Buried heterostructure laser with Fe doped semi-insulating blocking junction.

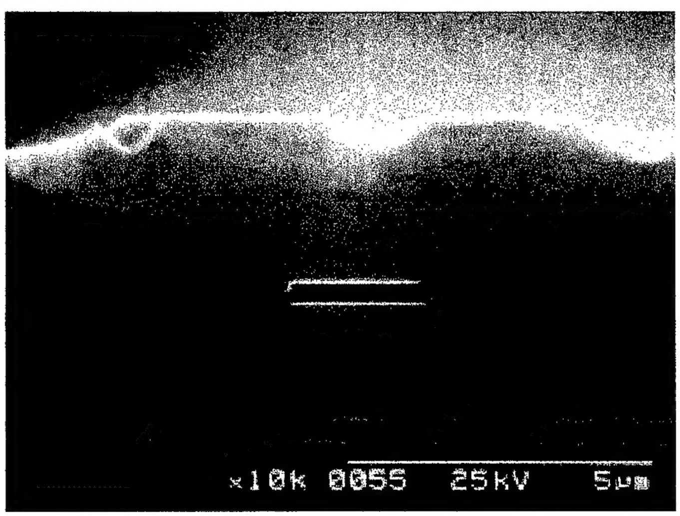

Figure 4. Scanning Electron Microscope cross section of SI-BRS laser.

So far we have developed the conditions for good selective regrowth without any mask overgrowth but more work remains to be done to optimize the doping profiles in order to obtain functional devices.

SGDBR Lasers With Integrated Amplifiers
A principle advantage of the sampled grating DBR over other widely tunable lasers is that it can be monolithically integrated with different devices such as semiconductor optical amplifiers (SOA's) and electro-absorption modulators to create complex photonic integrated circuits. Integration with an SOA can be difficult because of the need to achieve very high suppression of the facet reflections. To do this we have developed a SGDBR with an integrated SOA that has a curved passive output waveguide. A schematic of the device is shown in Figure 5. The principle advantage of the integrated SOA is that it can compensate for increased absorption loss in the mirrors at high tuning currents, and increase the output power from the device. Placing the power control outside of the laser cavity is highly advantageous since it decouples the output power control from the wavelength tuning characteristics.

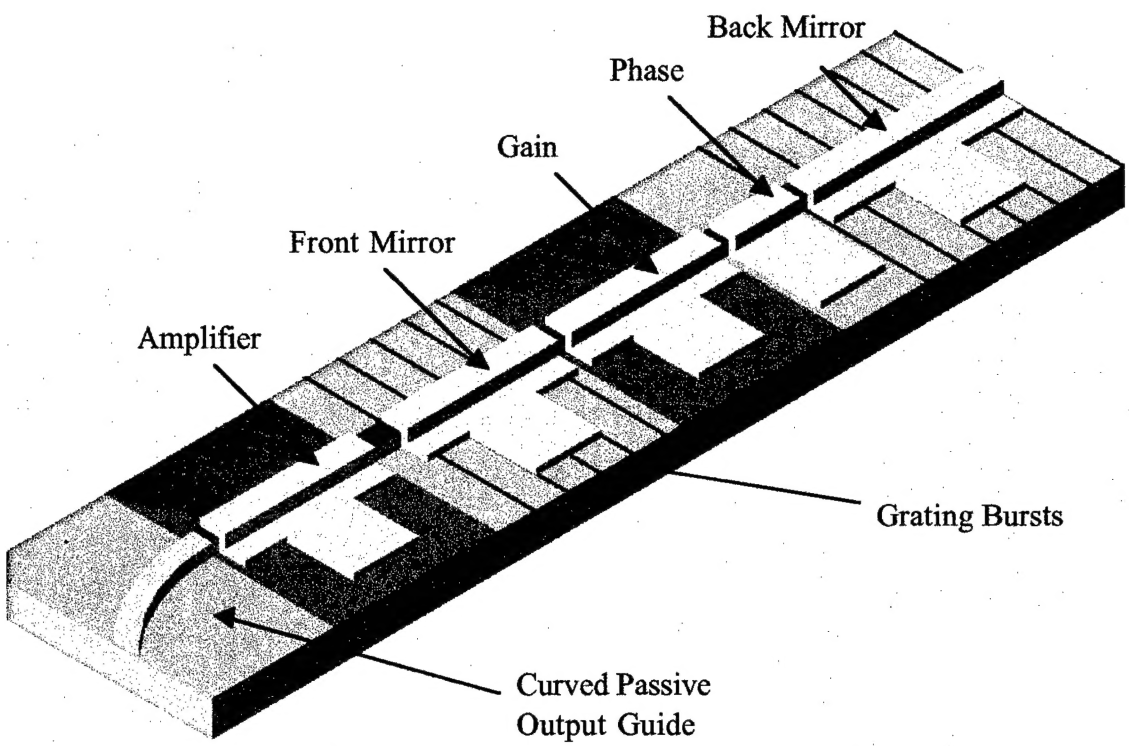

Figure 5. SGDBR laser with integrated semiconductor optical amplifier.

The key to successful integration of the amplifier is to suppress the output facet reflectivity to less than 1E-4. This is very difficult to achieve, especially over the entire 50 nm tuning range of the laser, even with the best multi-layer antireflection (AR) coatings. It is however relatively easy to achieve this by using an angled facet and a simple single layer AR coating. To avoid the difficulties associated with placing the entire device at an angle we use a curved passive waveguide at the output of the amplifier to create an angled facet. This gives a calculated facet reflectivity of less than 2.5E-5 over the entire 50 nm tuning range of the device when combined with a 1% antireflection coating. This low residual facet reflectivity enables the device to maintain a high side-mode suppression ratio even at relatively high amplifier gains. Better than 46 dB of SMSR was obtained at an amplifier gain of 8.5 dB.

The tuning performance for the front and back mirror are excellent for this device. Full wavelength coverage over 50 nm can be achieved with tuning currents as low as 15 mA for the rear SGDBR mirror and 14 mA for the front SGDBR mirror. These low tuning currents are achieved by optimum selection of the mirror design parameters. In this case a nominal peak spacing of 5.5 nm was used in the front mirror and 5.0 nm in the back mirror giving a repeat mode spacing of 55 nm. Despite the small difference in the mirror peak spacing between the front and the back mirror careful control of the grating kappa allowed better than 35dB SMSR to be maintained over the entire tuning range.

The saturation power for the integrated amplifier is greater than 6 mW for a bias of 150 mA. For all bias levels we begin to see gain compression once the input power exceeds 0.6 mW. The material transparency current density for the amplifier varied from 5.2 mA at 1570 nm to 14.3 mA at 1510 nm. Taking into account the waveguide losses we calculated the unity gain current at 1550 nm to be 14 mA and the peak gain to be 8.5 dB at 100 mA. Increasing the amplifier bias beyond this point increased the output saturation power but did not increase the gain. Varying the amplifier current from 0 to 150 mA enabled the output power to be varied over a 40 dB range without perturbing the laser wavelength. A similar change can not be achieved by varying the laser gain current without also adjusting the tuning currents to maintain the wavelength. This demonstrates the utility of the integrated amplifier, which provides both increased output power and improved wavelength stability.

SGDBR With Integrated EA Modulator

Widely tunable SGDBR lasers have potential applications in a wide variety of communications networks. Unfortunately the large optical cavities in these devices limit their direct modulation bandwidth to between 3 and 4 GHz. For data transmission applications these lasers must typically be operated with an extinction ratio penalty in order to ensure wavelength stability. They can also have fairly large chirp parameters for wavelengths which are detuned significantly from the band edge of the active region. External modulators have the potential to provide a higher bandwidth and lower chirp for data transmission applications. However external modulators increase the cost and complexity of a transmitter and can have significant insertion losses. To overcome this we have developed a monolithically integrated modulator for use with a SGDBR. The modulator section has the same waveguide structure as the passive and tuning sections in the laser. The same thick low bandgap waveguide that provides good index tuning makes an effective electroabsorption modulator. A cross section of the device is shown in Figure 6.

We fabricated a buried ridge stripe device with an integrated modulator. Electrical isolation between the different laser sections and between the laser and the modulator is achieved by removing the InGaAs contact layer and proton implanting. This implant is also used for lateral current confinement in the buried ridge stripe. The laser sections are separated by 10 µm long implants and the modulator is isolated from the laser with a 50 µm long implanted section. After implantation the sample is annealed at 410°C for 45 seconds to reduce the optical loss from the implant. It is important to keep the annealing temperature below 430°C to maintain the electrical isolation between the sections. The threshold current for the laser was 20 mA and the output power was 1.2 mW at 75 mA. The laser had a tuning range of 47 nm.

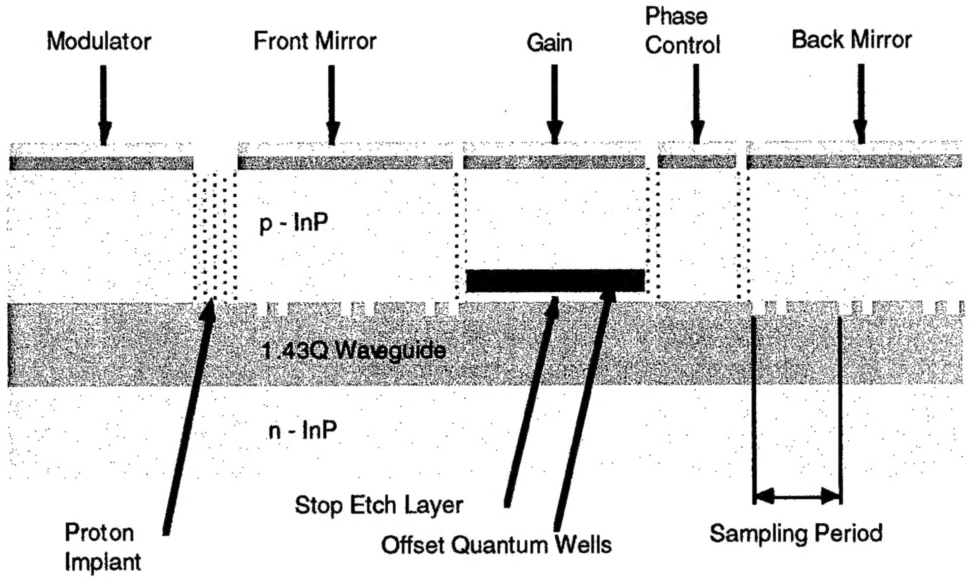

Figure 6. Cross Section of the Integrated Laser Modulator Device

The extinction ratio of the modulator as a function of reverse bias voltage is shown in Figure 7 for four different wavelengths that span the tuning range of the laser. The absorption increases monotonically for all four channels from 0.0 to -4.0V. The maximum extinction was 41.5 dB for 1525 nm at -4.0 V and the minimum was 22.3 dB at 1565.5 nm. There was no observable change in the wavelength of the output light over the entire range of bias voltages indicating sufficient electrical isolation of the laser and modulator sections.

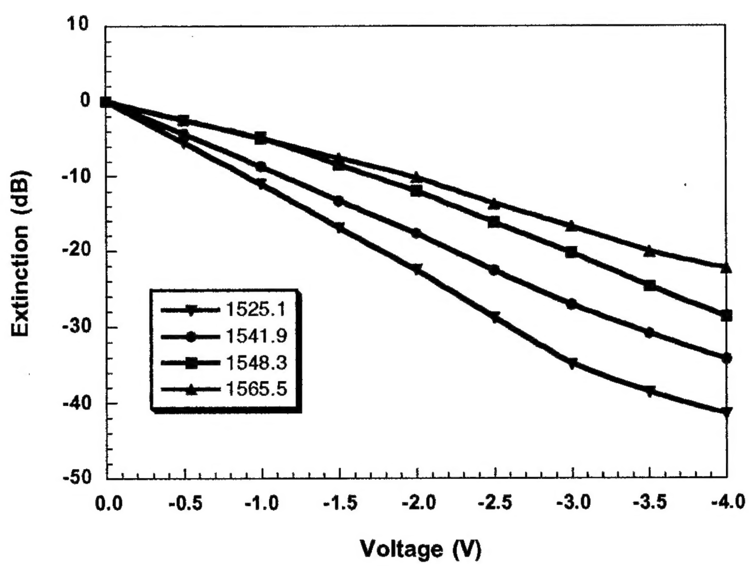

Figure 7. Extinction ratio vs. applied voltage for four different wavelengths.

Unfortunately the modulation bandwidth for the buried device was limited by the parasitic junction capacitance so no data transmission experiments were possible with this device. We also fabricated a ridge waveguide SGDBR with an integrated modulator. This device had a larger detuning between the laser wavelength and the modulator bandgap. The DC extinction curves is shown in Figure 8. A much higher voltage is required to achieve the same on off ratio with this device.

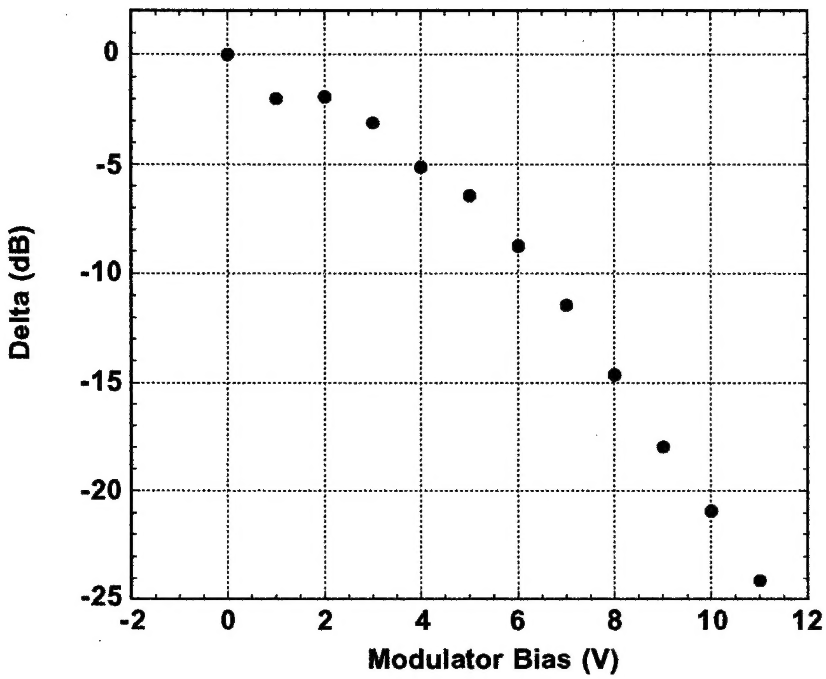

Figure 8. DC extinction curves for EA modulator at 1535 nm

The modulator was tested in back to back transmission using a –5.3V bias and a peak to peak drive amplitude of 5V. This produced an extinction ratio of 13 dB at 2.5 Gbit/s. Error free operation was achieved at a receiver power of –32 dBm using a pattern length of 2^{31}-1. The sensitivity at a bit error ratio of 1E-9 was –33.5 dBm (Figure 9). This was partially limited by spontaneous-signal beat noise from the erbium preamplifier. The optical filter bandwidth at the receiver was 1.3 nm which allowed excess noise to reach the receiver. There is also a small pattern dependent effect since the sensitivity was 1 dB better at a shorter pattern length of 2^{15}-1. Despite this, these results are significantly better than has been achieved with directly modulated SGDBR lasers. The eye diagram for a bit error ratio of 1E-9 is shown in Figure 10. This diagram shows symmetrical open eyes which are visible after the limiting amplifier. Future work will concentrate on reducing the drive voltage for the modulator by reducing the bandgap of the waveguide layer.

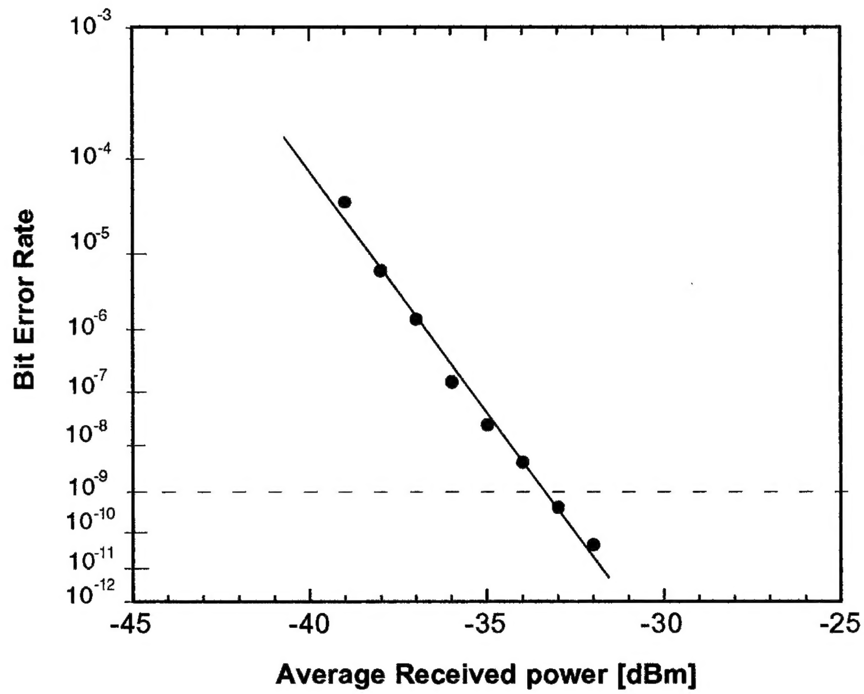

Figure 9. Back to Back Bit Error Rate Curves at 2.5 Gbit/s and 2^{31}-1 Pattern Length

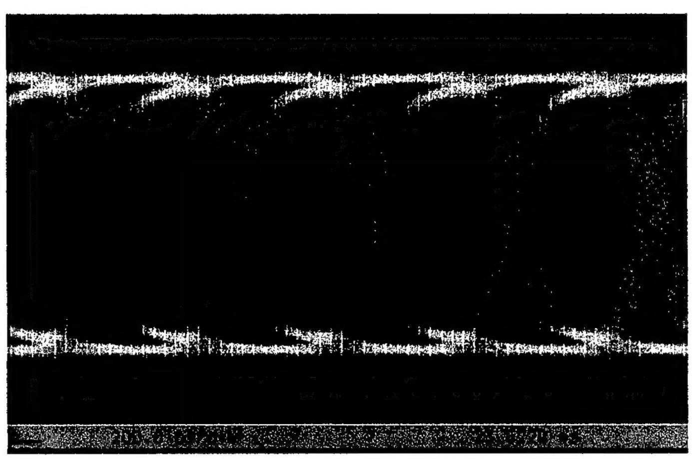

Figure 10. Eye Diagram at 2.488 Gbit/s Data Rate, 2^{31}-1 Pattern Length and 1E-9 Error Ratio

Future Work

The plans for the final year of this project are to concentrate on two different areas. One will be to work on control systems for the laser. These systems are required both to lock the laser to a desired operating wavelength and to lock the different sections of the laser to each other in order to ensure that the mirror peaks and the cavity mode are aligned. The other area of research will be in the development of the semi-insulating blocking junction regrowth. Using the Fe doped blocking junction a combination laser amplifier and modulator would be possible that had high modulation bandwidth low drive voltage and a wide tuning range.

Publications

"Widely Tunable Sampled Grating DBR Laser with Integrated Electroabsorption Modulator," B. Mason, G.A. Fish, S.P. DenBaars, and L.A. Coldren, *Photon. Tech. Letts.*, 11, (6), 638-640, (June 1999).

Conferences

"Monolithic Integration of a Widely Tunable Laser and an Electroabsorption Modulator," B. Mason, G.A. Fish, S.P. DenBaars, and L.A. Coldren, *Integrated Photonics Research '99*, Santa Barbara, CA, paper no. RME2, 53-55, (July 19-21, 1999).

"Characteristics of Sampled Grating DBR Lasers with Integrated Semiconductor Optical Amplifiers," B. Mason, G.A. Fish, J. Barton, L.A. Coldren, and S.P. DenBaars, submitted to OFC 2000.

"Data Transmission Performance of a Widely Tunable Electro-Absorption Modulator Laser," B. Mason, G.A. Fish, V. Kaman, J. Barton, L.A. Coldren, S.P. DenBaars, and